SEMICONDUCTOR MONITORING INSTRUMENT

The present invention relates to a semiconductor monitoring instrument, and in particular to an instrument for measuring the dynamic current-voltage conduction characteristics of a semiconductor device-under-test, especially at RF frequencies. The invention also relates to a method of such measurement.

For semiconductor devices of all types, including transistor devices, semiconductor LEDs and lasers and other semiconductor devices, there is a general requirement to be able to measure the conduction current-voltage (I-V) characteristics of a device to obtain a realistically representative picture of its I-V performance under operational conditions.

This applies to most types of transistor devices (discrete or integrated) including without limitation:

- bipolar transistors: NPN and PNP devices.[1]
- silicon FETs including MOSFETs (metal-oxide-semiconductor field-effect transistors) and LDMOS (laterally diffused metal oxide semiconductor).[1]
- MESFETs (metal-electrode-semiconductor field-effect transistors. Most commonly GaAsFETs when fabricated in GaAs).[2]
- HEMTs (high electron mobility transistors).[2]
- HBTs (heterojunction bipolar transistors).[1,2]

Note that devices marked [1] are generally fabricated in silicon (Si), silicon-germanium (SiGe) or silicon carbide (SiC), whereas devices marked [2] are generally fabricated using high-electron mobility compound semiconductor materials such as gallium arsenide (GaAs) or indium phosphide (InP).

Increasingly, modern electronic systems rely upon semiconductor devices operated under large-signal conditions. For example, mobile phone handsets, power amplifiers, base stations, radars, missile guidance systems/electronic instruments, and other like electronic systems use semiconductor integrated circuits (ICs) or discrete devices which are designed to operate under such large signal conditions, that is to operate over a large part of the available output I-V range. It becomes particularly important therefore that the I-V characteristics of the device are accurately characterised.

Traditionally, I-V characteristics of a semiconductor device have been measured either at dc, or under very slowly varying conditions. These are then supplemented by small-signal RF measurements to give an indication of I-V characteristics at higher operating frequencies. Increasingly, the approximation involved in this procedure is presenting a problem at higher (e.g. microwave or RF, i.e. GHz) frequencies, particularly in devices operating under large-signal conditions.

Almost all semiconductor devices exhibit significant differences between behaviour at higher, RF frequencies and behaviour under direct current (dc) or low frequency conditions. The difference in operational performance of devices can produce a large difference in operational performance of circuits and therefore of systems. In consequence, a circuit design based on dc measurements and built and operated at RF or microwave frequencies will often not perform as designed. As circuits have become more sophisticated, and in particular those operating under large signal conditions, the difference has become more significant.

Prior art systems of IV measurement, which rely upon extrapolation from dc or low frequency test conditions, are therefore no longer satisfactory.

It is an object of the present invention to mitigate some or all of the above disadvantages.

It is a particular object of the present invention to provide a measuring instrument and method for accurate measurement of the conduction I-V characteristics a device-under-test will possess at high (RF or microwave) operating frequencies to obtain a more realistic indication of I-V characteristics under real operating conditions.

It is a particular object of the present invention to provide, for transistor devices of all types and also semiconductor LEDs and lasers and other semiconductor devices, an instrument which can accurately measure the current-voltage conduction (I-V) characteristics of the device-under-test at a high-enough rate to inhibit dispersive processes from operating, yet at a low-enough rate to ensure that the measurements are free from reactive current flow components. The results of such measurements are referred to herein as the "dynamic I-V conduction characteristics of the device-under-test". A secondary objective is to measure the dc or "static" slow-sweep I-V characteristics as commonly made by many other instruments.

In accordance with the invention at its broadest an instrument for measuring dynamic I-V conduction characteristics of a semiconductor device-under-test comprises a means to apply a signal at two or more channels of a device-under-test, in particular at the input and output of a transistor or like device, comprising an adjustable dc bias and superimposed fast, generally rectangular synchronised bipolar pulses, and a means to measure the current response thereto at each of the two or more channels.

As indicated, within this industry there is a great desirability to be able to determine a properly representative measure of the RF or microwave

behaviour of the device from "simple" dc measurements - including pulsed dc measurements. More precisely, this requires the retrieval of charge or capacitance functions from conduction measurements to produce an RF-complete FET (or HEMT, or bipolar) model from the pulsed measurements.

The invention creates the possibility of achieving this in admirably simple manner in that a user can extract, recover or re-construct the true large-signal capacitance (or charge) functions from conductance measurements produced by the device.

A current/ voltage source is provided at each of two or more channels, for example at input and output, which applies a signal combining an adjustable dc bias and a pulsed element comprising, superimposed thereupon, a series of fast, generally rectangular bipolar pulses. Each pulse is generally rectangular in particular in its lead profile, having a rise time very much less than effective total pulse length. As discussed below the tail profile is less critical. Pulses are synchronised so that a pulse is applied at each channel simultaneously. Signals at each channel are thus synchronised in time but may be separately variable in amplitude, in particular in that both each dc bias and each pulse amplitude can be independently variable. A pulse amplitude may be any non-zero value, positive or negative, superimposed on the dc bias to generate a bipolar signal.

It should be understood that the reference to a signal having "superimposed" dc and pulse elements is intended to be descriptive of the effective signal profile at the device only. It is not meant to imply that the bias and pulse elements of the signal are separately generated and identifiably superimposed at some stage by the apparatus. Although such a means of generating the desired signal can be convenient in many instances, the invention is not limited to such cases, but extends to all cases where the desired signal profile

is applied, however generated, to two or more channels of the device-under-test in the described synchronous manner.

In principle, I-V curves at RF or microwave frequencies could be measured using any wave form that had a fast enough rate. The problem is one of interpretation. To recover the desired characteristic I-V curves it is necessary to apply a measurement technique which gives the characteristics of the device itself, uncorrupted by and completely independent of the method or instrument used to make the measurement. In other words, we need to apply a wave form which admits of ready interpretation of the response. Accordingly, the invention uses step pulses with flat tops up to the point of sampling to give a generally square form to the pulse. This requires a rapid rise to the flat top condition. However it will be appreciated that it is only the lead profile of the pulse that needs this generally square form, since any degradation of the pulse profile on the tail side occurs after sampling and is not material to the device response.

Preferably, the pulse wave form applied by the instrument is essentially critically damped so as to achieve a minimum rise time up to the point where the pulses become substantially flat. There is a further general requirement that the pulses to be applied must provide a high degree of isolation of the instrument from external influences that would otherwise degrade the performance.

Preferably, the measuring instrument further comprises means to measure dc I-V conduction characteristics of a semiconductor device-under-test by applying a dc signal at both the input and the output of the device-under-test.

In this preferred embodiment the instrument is therefore capable first of measuring the dc I-V characteristics, and also, by allowing a single bias point

to be set and then, starting from there, allowing all operating or instantaneous I-V points to be accessed or measured by application of the bipolar pulse bias, to obtain a representative indication of the dynamic I-V conduction characteristics. In accordance with the invention stepped pulses are applied to both input and output and the current at each point is measured quickly. The invention therefore requires two pulses each of which can be of either positive or negative sense and separately variable, that is two synchronised bipolar pulses.

The particular problem encountered at RF and microwave frequencies is that of applying a suitable biasing pulse, maintaining the pulse shape and integrity, and rapidly measuring current responses, whilst at the same time achieving device stability. At these frequencies, practical devices tend to undergo spurious oscillation when under test, which the skilled person will appreciate is one of the primary reasons why large-signal I-V testing has conventionally been carried out at low frequency or dc.

It has been suggested in the prior art that higher frequency pulses could be applied while keeping devices stable by use of a "bias tee". However, the capacitances within such as bias tee give the bias tee itself its own frequency response, which in practice limits the speed of the pulse which can be used. By contrast, in the present invention, fast step, generally flat topped pulses can be achieved at high pulse rates, and in particular with pulse lengths below about one μs, can be achieved.

In a particular embodiment of the invention, this is achieved in that the means to apply the adjustable bias at the input and output comprises a high stability voltage source serially connected to the input/output via a resistor, and preferably further serially connected especially at the input side through a low pass filter.

The power supplies are selected to have very low output impedances even at high frequencies well in excess of those present in the test signals.

The effect of this arrangement as incipient spurious oscillations arise will be understood. To spurious oscillation disturbances the near perfect power supplies appear to be shorts. The circuit therefore functions in effect as a resistive termination, and it is well understood that such a resistive termination is effective as a means of unconditionally stabilising a transistor or like device.

The resistor used to achieve this resistive termination must be very low in parasitic reactances. For a FET type device stabilisation on the output side is preferably achieved by a resistance in the range of a few Ω to some 10s of Ω, for example 5 Ω to 100 Ω. The resistance on the input side is preferably an order of magnitude greater, for example being some 10s of Ω to 100s of Ω, for example 50 Ω to 1000 Ω. For a bipolar type device resistances are likely to be an order of magnitude greater, for example 500 Ω to 5k Ω on the input side.

The inclusion of an optional low pass filter represents a second stabilisation measure which increases the effectiveness of stabilisation of the device-under-test at input and output. The low pass filter is selected such as to be effectively transparent at the pulse rates and rise times under test, but act to inhibit time dependent variations in current or voltage at higher oscillation frequencies.

Conveniently, the resistance is followed by a series inductor and a shunt capacitor to form the low pass filter.

Sample measuring points are provided across the resistor. In particular, current and/or voltage measuring means are provided to measure input and response currents and voltages at high speed, preferably within 5 ns, and in particular within 1-2 ns. Input and output pulse generators may be in the form of operational amplifiers having output impedances kept low preferably no more than a few Ω, for example less than 5 Ω, and in particular below 1 Ω, even at RF and microwave frequencies. This enables short pulses to be generated, preferably below 100 ns, and for example down to a few tens of ns.

However, although pulse lengths down below 1 μs, and in particular down to the order of 100 ns, are desirable in any event, it will be apparent to the skilled person that as indicated above a key parameter is also the speed of measurement. If measurement can be effected as quickly as the order of a few 10 ns, and more preferably still of the order of a few ns, from the beginning of the pulse then the *effective* pulse length as far as the device is concerned is reduced accordingly. The extent to which such a rapid measurement can be taken depends critically upon the profile of the leading or rising edge of the square wave. Once the measurement is taken it actually becomes entirely academic how the wave form decays. For practical purposes we can say that the rise time at the leading edge of the square wave needs to be one tenth or less of the effective pulse time. Where we rely on this fast sampling technique it correspondingly follows that the rise time must be less than one tenth of the time after pulse commencement where a sample is taken.

It will be appreciated that at the voltage/current levels required for many of the devices which it is envisaged to test it is impractical with current integrated circuit technology to get rise times below a few tens of ns.

However, in accordance with a preferred embodiment of the invention, a very fast effect pulse rate can be obtained by using a mechanical switch in

conjunction with a short sampling period. In accordance with the invention, the means to supply a variable bias for superposition onto the fixed bias, rather than being a pulse generator to generate the desired wave form, comprises two separate dc supplies, each with separately variable amplitude, the first supplying the dc bias in accordance with the principles of the invention and the second the fast pulse voltage, and a means to selectively apply and disapply this second dc supply so as to produce an effective square-wave pulse. The second dc supply may be applied as a superimposition on the first to generate a pulse, or as an alternative to the first to generate a pulse, with the switch being configured accordingly.

The means to selectively apply and disapply the second dc supply is conveniently a fast switch. To obtain an effective square pulse it is desirable that rise time is very short compared with the pulse length. It will then generally be desirable that fast switching, for example with a switching time between states of down to a few tens of picoseconds, can be achieved.

Since only a simple switch is now required rather than a complex operational amplifier, very fast effective pulse generation is possible. The switch can be electronic, electromechanical or mechanical. In each case switching over a time period below about 1 ns is possible, making sampling times of the order of a few ns practical. However at the large power levels at which modern devices can be operated, such switching times are not always readily achieved electronically, and in such applications a fast electromechanical switch such as a fast relay and for example a mercury reed relay, might be preferred.

To achieve fast sampling times and thus fast effective pulse lengths, current and/or voltage measuring means are operatively coupled to the said switch so as to make a high-speed measurement within the said period of a few ns after

actuation of the switch. The effective pulse length experienced by the device is thus reduced yet further to the order of a few ns.

The skilled person familiar with high-accuracy dc measurements will have an expectation that pulsed I(V) measurements should be made using four-point probe (or Kelvin type) methods. These are effective in reducing the effect of parasitic series resistances attributable to cabling and the like between measuring instrument and device-under-test which are the dominant problem at dc or low frequencies.

Parasitic series resistance, errors arising from which would be eliminated by a Kelvin four-point probe method, is far from being the most troublesome source of error in pulsed measurements. The main problems in this instance include parallel capacitance (including the capacitance of any connecting cable); and series inductance (including the inductance of any connecting cable).

To mitigate these problems, in a preferred embodiment the length of any connection between the device-under-test and the response measuring means in the measuring instrument is kept to a minimum, in that a remote head is provided including at least the response measuring means which may be connected to a primary supply and control means by remote cable, but to which the device-under-test may be directly connected. This direct connection eliminates the need for connecting cables and the like, and mitigates the problems outlined above.

For similar reasons, the remote head may comprise additionally or alternatively the means to apply the signal, or at least that a part thereof for example comprising the means to generate the superimposed fast, generally rectangular, synchronous bipolar pulses.

This last alternative is a particularly preferred feature wherein the fast pulses are generated by a fast switching arrangement as above described. In this case the effectiveness of the switching is maintained if the cable connection between the semiconductor device-under-test and the pulse generator is kept to a minimum. Accordingly, the pulse generator, and optionally also the response measuring means, are preferably provided in a remote head which may be connected to a primary supply and control means by remote cable, but to which the device-under-test may be directly connected.

In accordance with a further aspect of the invention, a method for measuring dynamic I-V conduction characteristics of a semiconductor device-under-test comprises applying an adjustable dc bias and superimposed fast, generally rectangular synchronous bipolar pulses at two channels, at for example the input and output of the device-under-test, and rapidly measuring the current response thereto at the said two channels being for example the input and output of a transistor or like device. The method in particular comprises use of the instrument as above described.

Preferred features of the method and preferred or necessary parameters for the bipolar pulse, pulse rates, measurement times etc will be understood by analogy with the foregoing description of the preferred embodiments of the instrument.

The invention will now be described by way of example only with reference to Figures 1 to 17 of the accompanying drawings wherein:

Figure 1 is an illustration of a comparison of typical dc and high frequency characteristics for a typical device to be tested;
Figure 2 illustrates the principle of resistively terminating a FET;

Figure 3 illustrates an arrangement for an embodiment of the invention supplying test signals at the drain of an FET;

Figure 4 illustrates an arrangement for an embodiment of the invention supplying test signals at the gate of an FET;

Figure 5 illustrates an effective equivalent circuit to Figures 3 and 4 as far as spurious noise oscillations are concerned;

Figures 6 and 7 illustrate preferred input and output pulse generators;

Figures 8 and 9 illustrate an example circuit in accordance with the invention for measuring the input side of a bipolar transistor;

Figure 10 illustrates the problem of stray shunt capacitance;

Figure 11 illustrates schematically an example of a remote measuring head for use with a device-under-test;

Figures 12 to 14 illustrate an embodiment of the invention adapted to produce particularly short pulse lengths of the order of 1 ns;

Figures 15 and 16 illustrate alternative arrangements by which fast effective pulses can be generated using fast switching;

Figure 17 illustrates the value of using a remote head for at least the data measurement means, and preferably also for the input signal generation.

The figures relate to an example instrument in accordance with the invention which embodies a scheme for enabling simultaneously bias + pulses + device stability.

Typical output characteristics for a semiconductor device-under-test are shown in figure 1. In this figure solid curves are dc ("static") characteristics, broken curves are dynamic i_D (i_C) - v_{DS} (v_{CE}) characteristics, o is the bias point, I_D (I_C) and V_{DS} (V_{CE}) are respectively the dc currents and voltages, and i_D (i_C) and v_{DS} (v_{CE}) are respectively the dynamic currents and voltages.

The different notations illustrate the application of the measuring device to different test devices, and refer to either FET or bipolar types of transistors. For an FET or like device reference is made to drain (D), gate (G) and source (S) whereas for a bipolar or like device reference is made to collector (C), base (B) and emitter (E). The principles of operation are generally the same and will be understood by the skilled person.

A measuring device in accordance with the invention applies the dc bias point "o" and also provides superimposed ("bipolar") pulses around this bias point to the device-under-test.

However, parasitic impedances arise in series with the gate (or base) and with the drain (or collector). Also there are parasitic impedances from these terminals to ground. These impedances arise inevitably from the device-under-test itself, from jigs supporting the device-under-test, from the measuring instrument, connecting cable, etc. The existence of these parasitic impedances means that the device-under-test is subject to a risk of oscillation.

This is a significant problem which has rendered attempts in the prior art to use higher frequency pulse-based measurement techniques impractical. Meaningful measurements cannot proceed with an oscillating device. The question therefore arises as to how to achieve device stability. With the device in accordance with the invention arrangements are made to precisely ensure stability. How this is achieved is discussed below.

In order to stabilise a transistor unconditionally microwave engineers may resistively terminate the output of the device - drain to ground for an FET and collector to ground for a bipolar. This principle is illustrated in figure 2. Although an FET transistor is shown it will be understood that the same approach is also applicable by analogy to a bipolar type device.

It is a key feature of the present invention that the device is adapted to mimic this principle, preferably at both input and output.

Figure 3 illustrates how this is achieved in the example device on the output side.

R_D must be low in value, typically from a few ohms to some tens of ohms. The resistor must also be very low in parasitic reactances.

SP1 and SP2 are sampling points. From measurements at these points, using A - D sampling, the voltages V_{DS} and v_{DS} are obtained. Then, because these voltages are measured across the almost pure resistor, their difference leads to the currents I_D and i_D - and this i_D is the required conduction current.

Hence R_D performs two functions simultaneously:

(i) the stabilisation measure, and;

(ii) the means of current measurements - both dc (I_D) and dynamic conduction (i_D).

Figure 4 illustrates how this is achieved in the example device on the input side (gate or base).

The device is arranged electronically in similar manner to that described on the output side. The example device now measures the voltages at the sampling points SP3 and SP4, hence the potential difference across the resistor R_G, which yields the conduction currents I_G and i_G (or I_B and i_B for a bipolar). Again the choice of R_G is critical, being some tens to hundreds of ohms and very low in parasitic reactances.

A very important feature is that the introduction of the low-pass filter (LPF) represents a second stabilisation measure.

As far as spurious "incipient" oscillation or noise signals are concerned the circuit appears as shown in Figure 5.

The low-pass filter (LPF) has to be transparent at the pulse rates and rise times attendant to the measurement, but also must be such as to quench and inhibit time-dependent variations in current or voltage at higher (oscillation) frequencies.

In practice the LPF is realised as a combination of shunt capacitors and series inductors in the gate (or base) lead.

This arrangement:

- Keeps the device-under-test stable.
- Allows input and output conduction currents to be measured under dc and dynamic conditions.
- Allows dc biases and pulses to be applied simultaneously to the device-under-test.
- Allows fast (few tens of nanoseconds rise time) pulses to be applied.
- Provides a measure of buffering or isolation of the device-under-test, which preserves the pulse shape and integrity.
- Provides a measure of protection from device destruction by current runaway - especially with bipolar devices.
- Provides a measure of short-circuit protection for the measuring instrument.

There are also important special aspects regarding the pulse generators, at both the input and the output sides. These are indicated in Figure 6. These generators may be realised in practice in the form of operational amplifiers (op amps), as shown in Figure 7, which illustrates both an input op amp (left) and an output op amp (right).

The important requirement is that for each op amp the output impedance Z_{out} must be kept extremely low - even at RF and microwave frequencies. For this the op amps need to be specially selected.

The consequence is that this scheme allows short pulses to be generated - down to a few tens of nanoseconds (ns).

Bipolar Transistor Measurements present particular difficulties. Figures 8 and 9 illustrate the principles of an embodiment of the invention in measuring, at constant base current I_B, the dynamic I-V characteristics of bipolar transistors - which are notoriously unstable.

There are two important issues;

(i) How to measure the dynamic I-V conduction characteristics with I_B constant as parameter, whilst keeping the device stable.

(ii) Defining the measurement conditions for valid measurement of the dynamic I-V conduction characteristics uncorrupted by the reactive effects.

Considering issue (ii) first of all. The measurement conditions are satisfied by maintaining the pulse length greater than a time as defined by the following inequality:

$$t_{pulse} \geq t_{ON} = \frac{(\beta+1)i_{BSTEP}}{2\pi f_T\left(\frac{kT}{q}\right)} R_B \ln\left[1+\frac{v_{BEON}}{i_{BSTEP}R_B}\right]$$

In which: t_{ON} is the time required to fully turn the transistor on, β is the dc collector-to-base current ratio, f_T is the current transition frequency and all the remaining quantities are readily known. At normal ambient temperature ("room" temperature) T = 298K and the kT/q ratio is 0.025V.

There is one connection approach that might ideally be desired - but which cannot be achieved – which is to drive the base input from a constant current source. Microwave and RF engineers, will understand that this cannot practicably be achieved. At the high frequencies associated with the very short pulses open or short-circuit terminations (as for example are necessary with h-parameter or y-parameter characterisation of the device-under-test) are infeasible.

(Under small-signal linearized conditions one can measure S-parameters and then transform the results into h, y, z ABCD or other sets of parameters. However, under large-signal conditions this cannot be done.)

So, for measuring a bipolar transistor, what has to be established is the type of circuit indicated in Figure 8. As before, sampling points SP5 and SP6 are immediately followed by A > D converters within the measuring instrument.

Regarding Z_B; this required series impedance is:

(a) realistic in the practical case, and
(b) needed for device-under-test stability.

With Z_B it is now possible to measure directly what is required, as follows:

In the illustrated example Z_B is realised as resistor R_B in series with a low-pass filter (LPF), indicated in Figure 9.

R_B is typically a few hundreds of ohms in value and it must also be very low in parasitic reactances. Note that the value range is around an order-of-magnitude larger than for R_D described in conjunction with measurements on FETs, see above. The LPF has to be "transparent" at the pulse rates and rise times in use. In this method fast-sampling is used at the SP5 and SP6 points. V_B, v_B are iterated (digitally) until I_B, i_B are as set - or as desired.

Figure 10 illustrates an embodiment of the device specifically relevant to measurement at very low i_B values - in the region of $1\mu A$ order of magnitude.

The stray instrument capacitance C_{STRAY} represents a problem and special low-capacitance buffering techniques, internal to the measuring instrument, are required to keep the effective stray capacitance low - down to the order of a few pF. As this stray capacitance is made smaller, so i_B can be set ever smaller - within known accuracy limits.

For contacting to the device-under-test outside the instrument there are two possibilities:

(i) for packaged devices: a cabled connector and the device jig, and:
(ii) for bare chips: a cable run followed by an RF on-wafer prober.

These RF probers are precision units and lower frequency needle probers are completely useless in this RF or microwave context.

There is, however, a problem with the total series inductance and the total shunt capacitance of the cable connecting to the wafer prober. . A degree of flexibility in balancing the effects of these unwanted impedances and capacitances can be had by using cables that are available with characteristic impedance between 10 Ω and 95 Ω. Care must be taken regarding the selection of the minimum pulse period and often 100 ns cannot be used.

In order to minimise this problem a remote head (11) is installed on the same micromanipulator as the RF on-wafer prober (12). The arrangement is shown in circuit-schematic form in Figure 11.

Figure 12 illustrates an embodiment of the device specifically adapted for pulse lengths having an order of magnitude of a few nanosecond.

A feature is exploited when the device-under-test is a bipolar transistor which makes use of stray capacitance in the connecting cable run. This enables effective pulse lengths to be generated down to the order of a few ns, by relying on the principle that the effective pulse length constitutes the time between the device-under-test turning ON and the sampling point, and that the only real limitation on reduction of this effective pulse length is the need for the sampling time to be an order of magnitude bigger than the rise time.

The effect to be exploited assumes that a connection is made using a cable run that is predominantly capacitive as illustrated in Figure 12. This is approximately equivalent to the simple circuit shown in Figure 13 which shows the current i_{CAP} that flows in the capacitive element of the cable.

The key aspects are:

(I) Start from $v_{BE} = 0$ (i.e. $i_B = 0$), then:

(II) Turn the pulse on - from a current generator source.

The waveforms of Figure 14 show the effects - remembering that $i = C\frac{dv}{dt}$

The time t_{ON} can be ascertained by continually sampling (since when $i_B = 0$, $i_C = 0$). The sample acquisition time is around 1 to 2 ns. Therefore it is possible to sample i_C and this enables measurements at effective pulse lengths down to as low as the order of 1 ns.

Figure 15 shows an alternative input to generate particularly high effective pulse rates. In the previous examples, pulses were generated by combined application of a dc bias and of a pulsed wave of suitable form applied by, for example, an operational amplifier. At the large operating voltages and currents necessary to test typical modern FET and bipolar transistors and other devices for high power applications, it is unlikely to be practical with present technology to generate and transmit or deliver via cables pulse lengths below the order of one or a few hundred ns. Although the foregoing example gives a method of getting low effective pulse lengths for bipolar transistors using the stray capacitance of the cable, such an effect could not be exploited for FETs.

In this example the underlying bias is applied by a first dc source (S1), and the "variable", pulse bias is applied by a second dc source (S2). A very fast switch (23) is used to switch in the second source. In the example, a mechanical mercury wetted reed relay switch is used which allows a switching time of well below 1 ns. With this sort of rise time, this can give an effective square wave pulse (or at least the forward part thereof) at high power without actually generating the pulse electronically. It becomes possible to gain an effective reading after a sample time (and therefore after an effective pulse length from the prospective of the device) of a few ns, and possibly even as low as 1 ns or

less. As with the previous example, this example exploits the point that all that functionally matters in accordance with the invention is the profile of the leading edge of the square wave and the effective pulse length created by the sample time.

In the example a second switch (24) isolates the first source. It will be apparent that an effective square wave can be generated either by superimposition of S1 and S2 or by rapidly selectively switching between S1 and S2 dc signals of different amplitude. Figure 16 shows an alternative switch (28) for this latter function. In all cases to avoid stray capacitances in cabling degrading effective rapid pulse rise, the distance to the DUT is kept as short as possible, and in the example the switching is included with suitable control electronics and sampling means (not shown) in a remote head (26) providing for direct connection to the DUT.

It is also useful to take measurement via a remote head, for example to minimise spurious results attributable to parallel capacitance from the capacitance of any connecting cable and series inductance from the inductance of any connecting cable. For some applications, an instrument in accordance with the invention preferably provides a remote head for direct connection to the DUT which includes such measurement means. Depending on application this remote head for sensing may additionally embody the signal generation means, or at least the pulse generation means such as the switches, described above.

Figure 17 illustrates the value of a remote head in such a case, the figure illustrating the bare principle of four-point probe measurements, and what becomes of it in a fast-pulse measurement.

At dc or very low frequency (Figure 17a) the main problem is that parasitic resistance (represented by the box 33) in cables, connectors and contacts gives rise to a voltage drop that adds to the voltage drop across the device-under-test (31), producing an error if the device voltage is measured at the generator (i.e. instrument) end of the cables. The answer is to measure the voltage right at the device, thereby implying four terminals as close as can be to the DUT itself: two to deliver the current to the device, and two to measure the resultant potential across it (V1, V2). This is the basis of the conventional four point approach.

If the same four-point probe approach is tried in fast-pulse measurements, there is an added complication. Parasitic capacitances and inductances in the cable run (represented schematically by the box 34) become an issue. There is a problem in particular with current, in parallel with the current the DUT (31) passes, flowing in the cable capacitance. Such a current constitutes an error current because it is measured, along with the desired device current, by the ammeter A (Figure 17b).

The answer to this problem, illustrated in Figure 17c, is to move the ammeter to the DUT side of the cable, where the four-point probe principle has already placed the voltage sensing points. What the resultant configuration amounts to is a complete remote-sensing head (35) (and, as an aside, the means for generating the pulses themselves may be incorporated in the head also, particularly if these are the switching apparatus of figures 15 to 16). A simpler alternative for early generation instruments is to retain both current and voltage sensing within the instrument itself and to develop some rules as to what cable and DUT mounting configurations are admissible as a function of pulse length.

CLAIMS

1. An instrument for measuring dynamic I-V conduction characteristics of a semiconductor device-under-test comprising a means to apply a signal at two or more channels of a device-under-test, comprising an adjustable dc bias and superimposed fast, generally rectangular synchronous bipolar pulses, and a means to measure the current response thereto at each of the two or more channels.

2. A measuring instrument in accordance with claim 1 wherein the applied pulse wave form is essentially critically damped so as to achieve a minimum rise time up to the point where the pulses become substantially flat.

3. A measuring instrument in accordance with claim 1 or claim 2 further comprising means to measure dc I-V conduction characteristics of a semiconductor device-under-test by applying a dc signal at both the input and the output of the device-under-test.

4. A measuring instrument in accordance with claim 3 wherein the instrument is therefore capable first of measuring the dc I-V characteristics, and adapted to set a single bias point based on measured dc I-V characteristics and to use this bias point as a starting point to access or measure all operating instantaneous I-V points by application of the bipolar pulse bias, to obtain a representative indication of the dynamic I-V conduction characteristics.

5. A measuring instrument in accordance with any preceding claim wherein the means to apply an adjustable bias at both the input and the output the

output of a device-under-test comprise a means to apply a pulse at each of the input and the output each of which can be of either positive or negative sense and separately variable, that is two synchronised bipolar pulses.

6. A measuring instrument in accordance with any preceding claim wherein the means to apply the adjustable bias at the input and output comprises a high stability voltage source serially connected to the input/output via a resistor.

7. A measuring instrument in accordance with claim 6 wherein the high stability voltage source is further serially connected especially at the input side through a low pass filter.

8. A measuring instrument in accordance with claim 7 wherein the resistance is followed by a series inductor and a shunt capacitor to form the low pass filter.

9. A measuring instrument in accordance with any preceding claim wherein current and/or voltage measuring means are provided to measure input and response currents and voltages within 5 ns, and in particular within 1-2 ns.

10. A measuring instrument in accordance with any preceding claim wherein input and output pulse generators are in the form of operational amplifiers having output impedances kept to no more than a few Ω even at RF and microwave frequencies.

11. A measuring instrument in accordance with any preceding claim wherein input and output pulse generators generate short pulses down to a few tens of ns in pulse length.

12. A measuring instrument in accordance with any preceding claim comprising a remote head including at least the response measuring means, to which ~~the device-under-test may be directly connected~~.

13. A measuring instrument in accordance with any preceding claim comprising a remote head including at least means to generate the superimposed fast, generally rectangular, synchronous bipolar pulses, to which the device-under-test may be directly connected.

14. A method for measuring dynamic I-V conduction characteristics of a semiconductor device-under-test comprising the steps of:
applying an adjustable bias signal comprising an adjustable dc bias and superimposed fast, generally rectangular synchronous bipolar pulses at two channels of the device-under-test;
rapidly measuring the current response thereto at the said two channels.

15. The method of claim 14 further comprising the step of measuring the dc I-V conduction characteristics of a semiconductor device-under-test by applying a dc signal at both the input and the output of the device-under-test.

16. The method of claim 15 comprising the steps of:
first measuring the dc I-V conduction characteristics of a semiconductor device-under-test by applying a dc signal at both the input and the output of the device-under-test;

using the measured dc I-V characteristics to set a single bias point;
accessing all operating or instantaneous I-V points from this bias point by application of the bipolar pulse bias;
measuring the response to obtain a representative indication of the dynamic I-V conduction characteristics.

17. The method of one of claims 14 to 16 wherein each of the input and output pulses is separately applied to be either positive or negative sense and separately variable, that is that the applied pulses comprise two synchronised bipolar pulses.

18. The method of one of claims 14 to 17 comprising use of the instrument of one of claims 1 to 11.

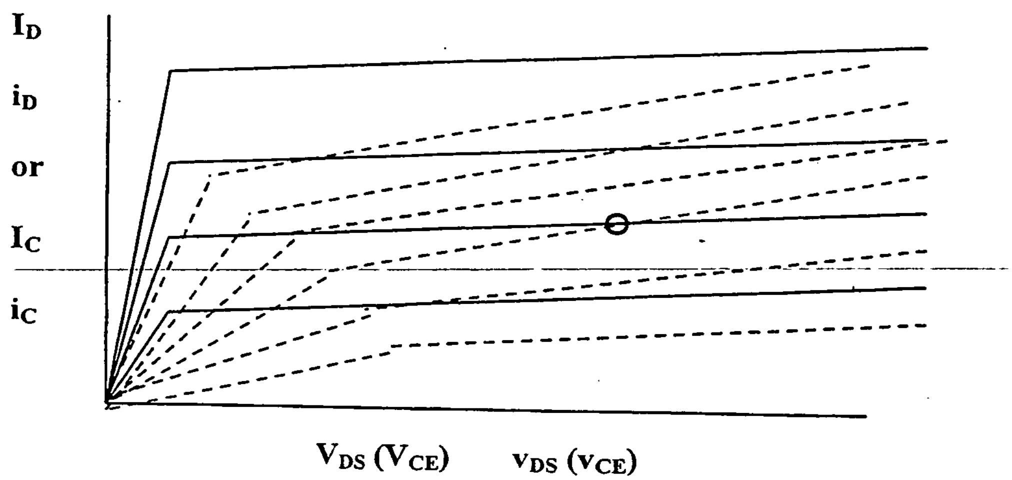


Figure 1

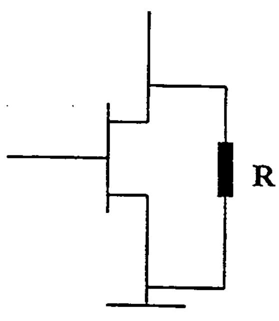


Figure 2

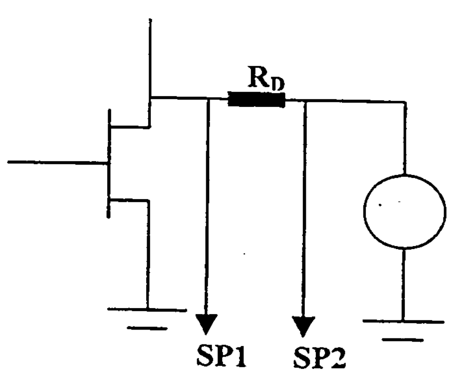
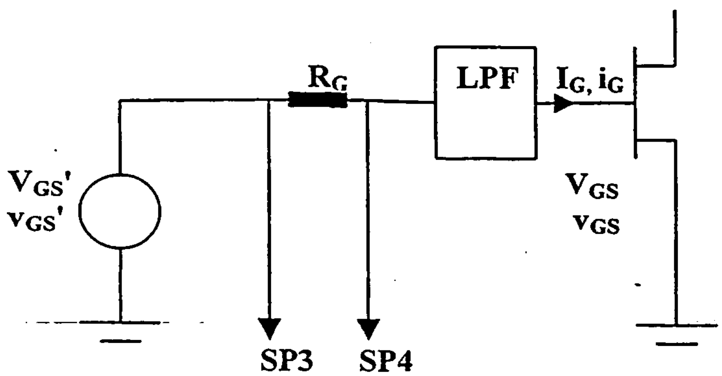


Figure 3



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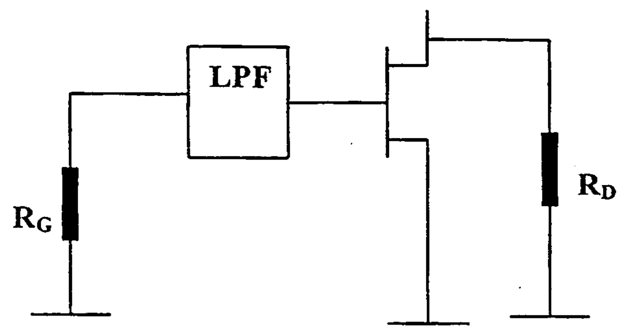
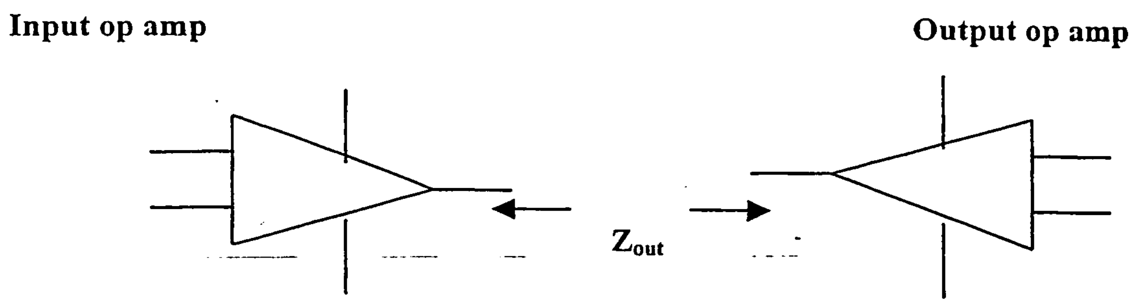


Figure 5

Figure 6



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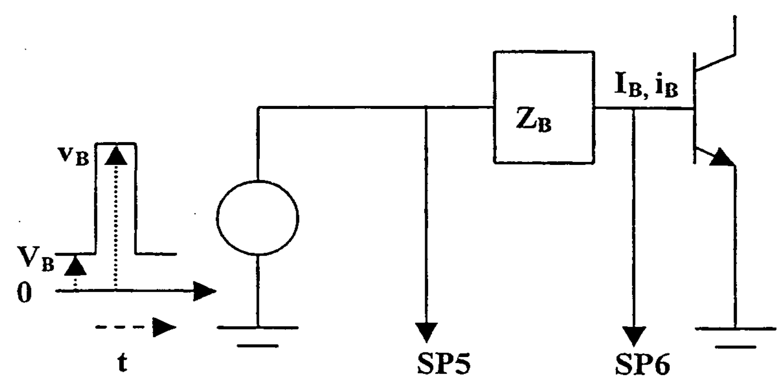

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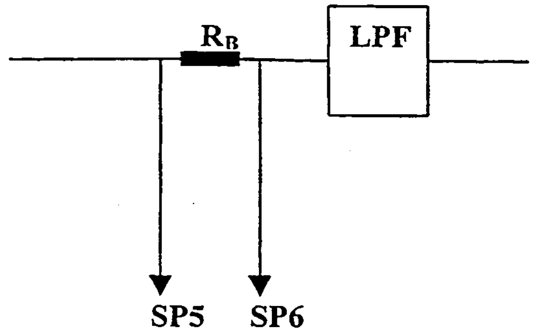

Figure 9

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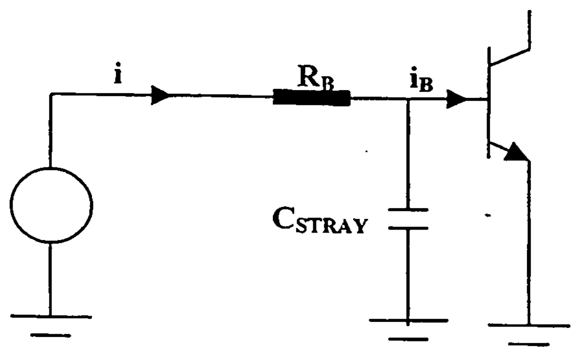

Figure 10

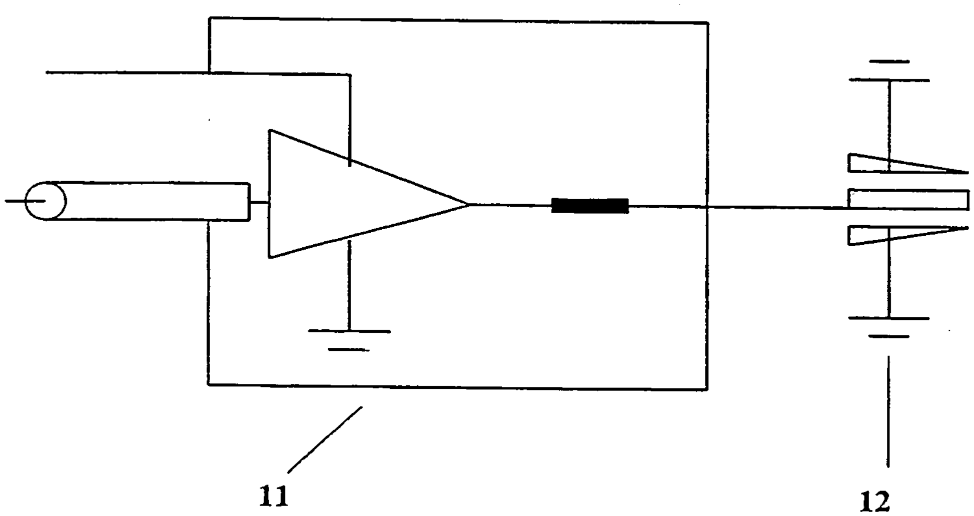

Figure 11

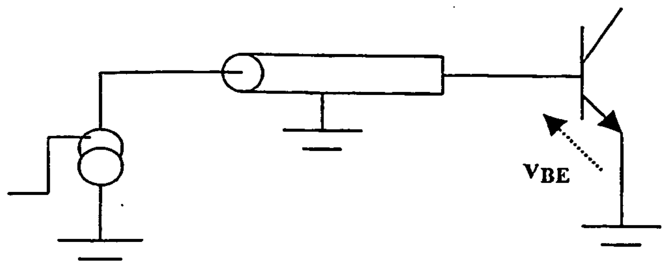

Figure 12

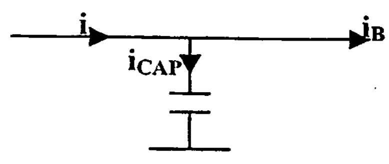

Figure 13

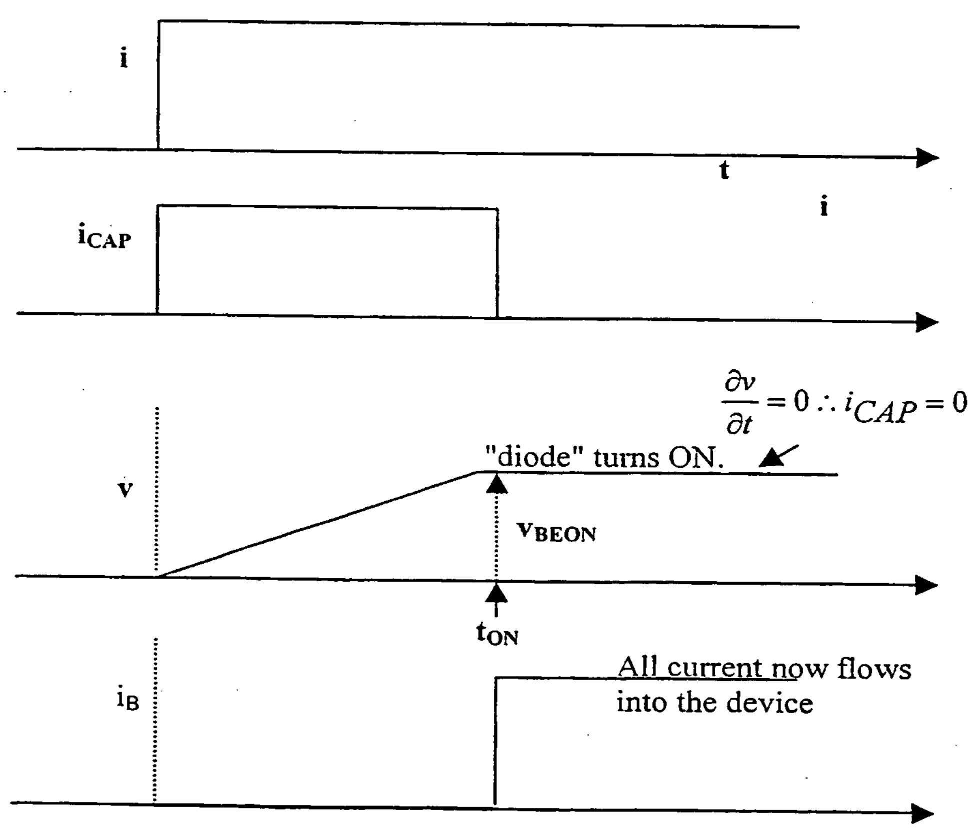

Figure 14

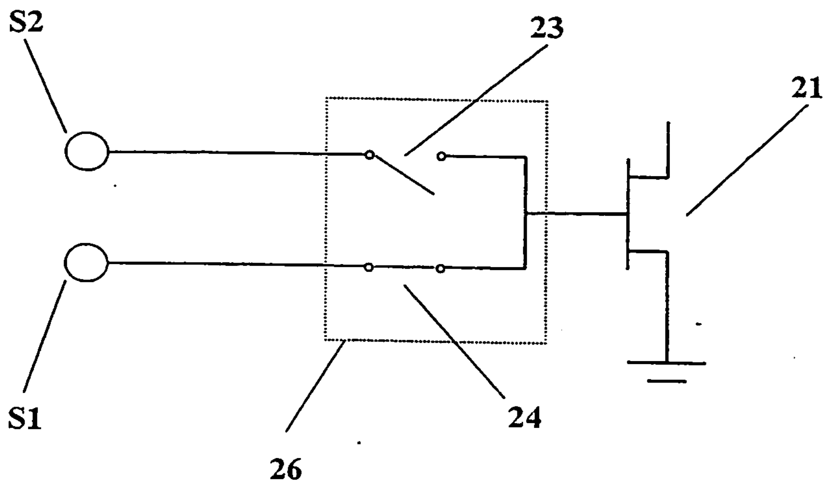

Figure 15

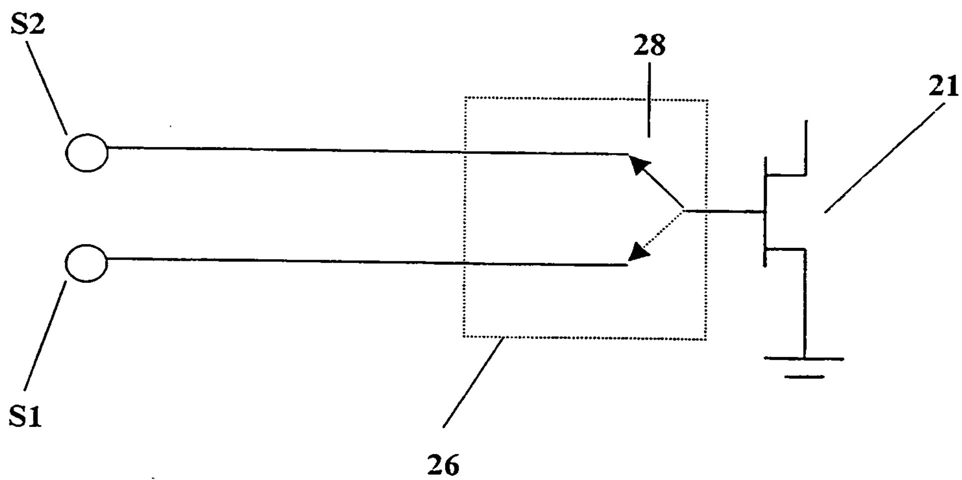

Figure 16

Figure 17a

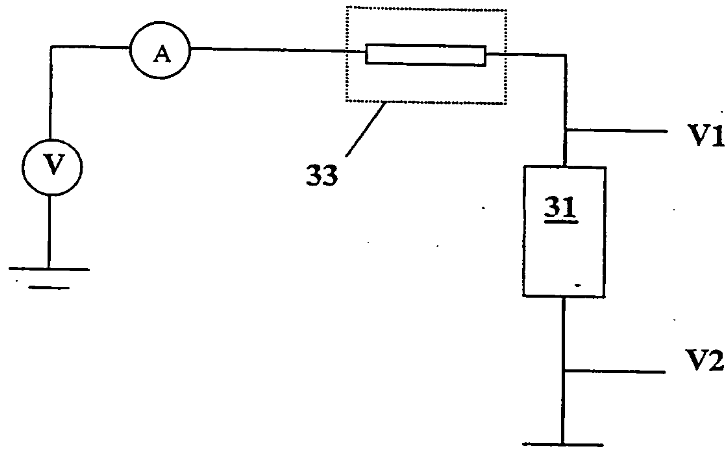

Figure 17b

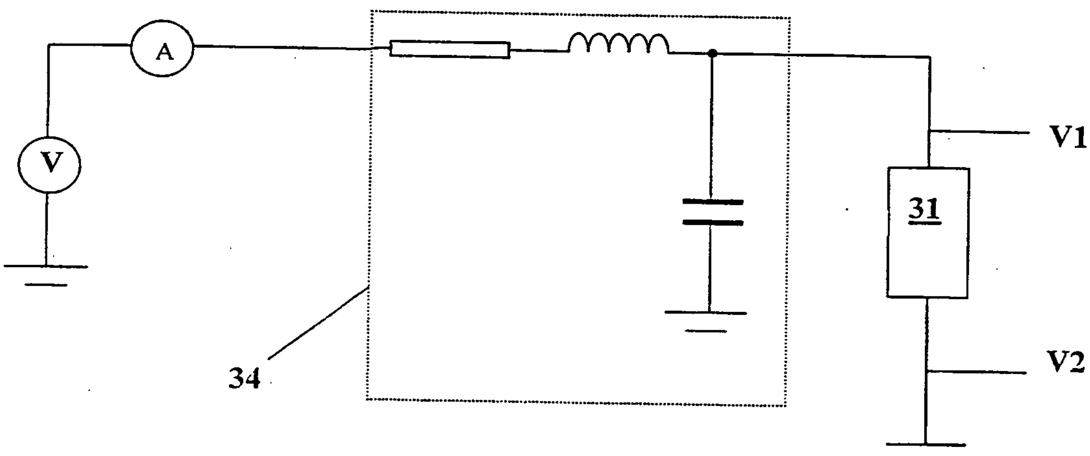

Figure 17c